Numerical Flow Analysis in actual model of Human Coronary

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Abstract: Due to importance of human being health subject ,concerning the mortality and its side effects created from cardiovascular diseases, studies has been shown that flow analysis of blood in coronary artery has a special role. This matter along with a vast efforts in the past, now and future that has been followed, resulted to have a better understanding and finally set a mechanism for more care and over coming the problem in a successful way.
In this study by indicating the main key factors such as velocity and wall shear stress , will solve the governing equations of fluid flow by fluent software on two normal right coronary arteries, and also considering the resulted, plots and diagrams in different modes and conditions of arteries, including steady and transient simulation, laminar and Turbulent flow regime by usage of Newtonian and non-Newtonian models .There Will achieve important results that the most important one is known as applying Newtonian model for approximation of viscosity of blood in all occasion for analyzing arteries except special cases that need careful study in specific circumstances.

Key-words: CFD, Coronary artery, Blood flow, WSS, Velocity distribution, Non-Newtonian model

1 Introduction

Cardiovascular diseases are considered one of the most common illnesses of present century and nowadays are the main causes of death in industrial and semi-industrial societies. It has been declared that the distribution of wall shear stress (WSS) in coronary arteries is an important factor in the onset of coronary diseases and asserted that atherosclerosis inside coronary vessels is dependant on WSS increase and fluctuation. (Myers [1], Kirpalani [2]) Researches on this field have been done in many branches in recent years. This resulted to have a better understanding and finally set a mechanism for more care and over coming the problem in a successful way. One of the most important of these studies is the one done by Barbara Johnston [3], [4], in which the coronary vessel is examined in both steady and pulsatile cases. Other important aspect of blood flow simulation is the consideration blood as a fluid and also this fact that blood shows non-Newtonian behavior in low strain rates (under 100/s) ([5], [6]).

Therefore it is necessary to use different models to examine blood viscosity in non-Newtonian way. The subject considered here is the governing equations and numerical analysis of blood flow on two samples of right normal coronaries in different circumstances including steady and pulsatile cases, laminar or turbulent flow regimes and using Newtonian and non-Newtonian models by fluent software. Further more stating the overall circumstances of analysis and necessity of vessel geometry reconstruction and at the end explain the obtained results.

2 Governing Equations of fluid flow

Continuity equation derived from mass conservation law:

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{1}$$

Navier-Stocks equations derived from second law of Newton:

$$\mu\left[\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right] = \frac{\partial p}{\partial x_i} + \nabla^{\text{r}} \mu(J) u_i + \frac{\partial \mu(J)}{\partial x_j}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] \tag{2}$$

Which includes 3 equations in X, Y, Z directions.

(t = time, p= pressure, u= velocity, μ =viscosity)

3 Vessel Geometry

Due to the fact that all vessels have significant differences with each other, to have more efficient and precise assesment, use of more realistic models is necessary. Also presenting proper methods for 3D simulation & reconstruction of vessels will help us to solving the governing equations of fluid flow throughout the cardiac cycle.
In this paper, direct use of different segments of images from the arteries that taken by 64-Slice CT-Scan is proposed. The analysis is based on transferring necessary data from the images to one of the CFD software packages to numerical solve of the governing equations. Strategy of geometry reconstruction is obtaining 3D components(x, y, z) of some proper and important points on each segment of the vessel, then transfer these points to Gambit software and get a string of circles and substantial points on vessel structure. By connecting these points the vessel shape is reconstructed [7].

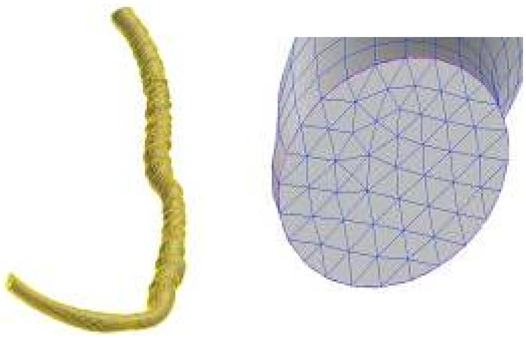

Figure 1 : sample of meshing in first artery

4 Non-Newtonian blood models

Blood is a complex non-Newtonian fluid in which its constitutive equation plays an important role in homodynamic and hemorheology. Two examined models in this study are as following:

1) power law models :

$$\tau = \mu \dot{\gamma}^n \quad (3)$$

(τ = shear stress, $\dot{\gamma}$= strain rate)

2) Carreau models:

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\left[1 + (\lambda\dot{\gamma})^2\right]^{(n-1)/2} \quad (4)$$

(n = 0.0.3568, T = temperature, μ = viscosity, λ =3.313)

5 Overall circumstances of analysis

The reason for solving governing equations is to find information for technical designing (e.g. velocity distribution) or information that introduces atherogenesis problems (e.g. WSS changes). The result of Starry H.C. study shows that “flow patterns and wall structure are the only two factors which might relate to the position of atheroma”. [8]
Assumptions of this study are:
At the inlet, the flow is fully developed, perpendicular to entrance, incompressible, steady & has uniform velocity profile. On the solid walls of the artery (which are assumed to be rigid), the no-slip condition is imposed on the velocities. At the outlet of the artery, the velocities are free, but the normal and tangential shear stresses are constrained to be zero and the gauge pressure is also set to zero.

6 Problem analysis cases

There are two approaches to analyzing these cases:

- Steady case
- Unsteady/Transient case

In the first case inlet velocity is considered constant and in velocities of 0.02, 0.05, 0.1, 0.2, 0.5 and 1 m/s the vessels are examined for sensitivity analysis. In the second case to simulate the transit condition, the equation of inlet velocity is needed .This request was granted by the diagram giving by Matsuo [9] which is drawn with inlet velocity versus time.

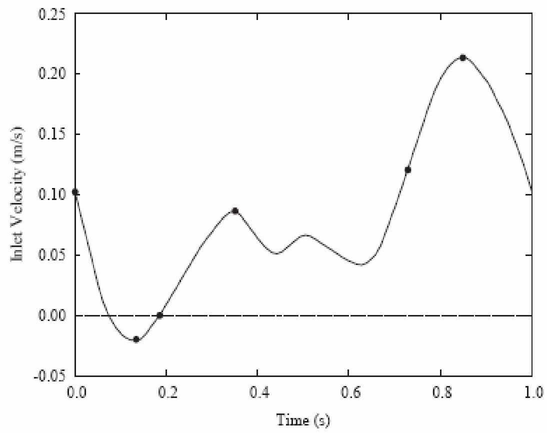

Figure 2: Inlet velocity profile in normal right coronary (Matsuo [9])

This simulation is done with the time steps of 0.01, 0.13, 0.18, 0.35, 0.72 and 0.85S during cardiac cycle. These are the key points in cardiac cycle as follows:

T= 0.01: near the beginning of cycle
T= 0.13: maximum reverse velocity
T= 0.18: is where the flow has stopped prior to the acceleration
T= 0.35: the peak of systole wave
T= 0.72: is approximately halfway through the rapid acceleration phase
T=0.85: the peak of diastole wave (maximum forward velocity)

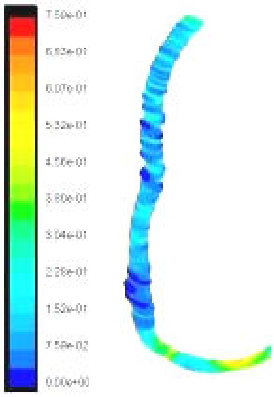

Figure 3: WSS distribution in Newtonian model with velocity inlet 0.02 m/s (first artery)

7 Observations

1) WSS patterns are same for each vessel with all Models (in all different inlet velocities) and the magnitude of WSS are different for each model. (Myers [1])
2) In both vessels, in considering of fluctuation of shear stress distribution almost observe the great increase at the distal end, and this is possibly due to the nature of the vessels which encountered with radius incrassation at the middle and decrease at the end. This is in agreement with studies of Myers [1] and Kirpalani [2].
3) Sudden expansions result low WSS for most cardiac cycles.

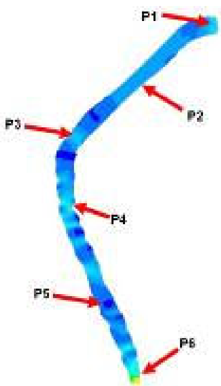

Figure 4: Selection of 6 arbitrary points on the second artery.

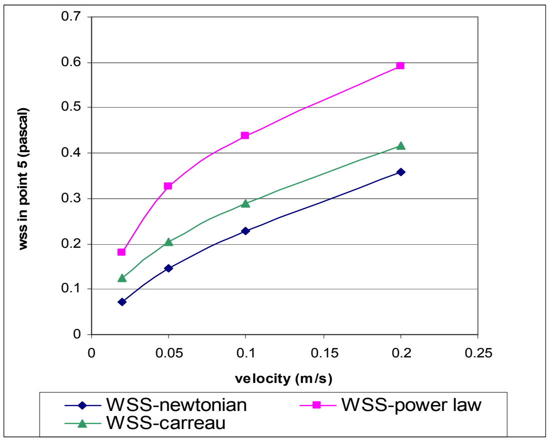

Figure 5: Magnitudes of WSS in p5 from second artery

In more accurate examination of WSS, in some points along the vessels interesting results were seen. In figures 4 & 5 a graph is shown which indicates the WSS changes at one of the mentioned points versus velocity changes.

It was observed that in low stress area magnitude of WSS is significantly higher in non-Newtonian case versus Newtonian and at low inlet velocities, distribution of WSS in power law model is more than Carreau model. As a result, utilizing non Newtonian models in low strain rate is necessary. In examining transient case, by extracting equations from Matsuo diagram, inlet velocity changes during cardiac cycle are found and solving the problem becomes possible. About pulsatile flow, significant difference is seen in WSS patterns when flow becomes slow or reverse flow is happening. This is in agreement with Asakura [10] observations, and like many other researches Myers[1], Feldman[11], Van de vosse [12] it can be proposed that WSS patterns averages during cardiac cycle is in good adaptation with steady flow patterns.

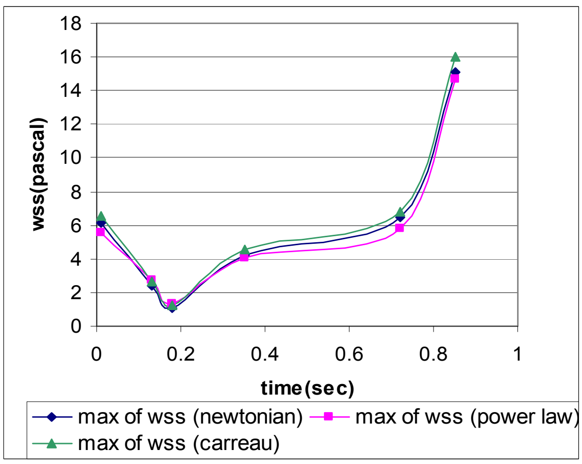

Figure 6: Distribution of WSS during Cardiac cycle (artery 1)

For better understanding of how the velocity is distributed, the image segments are shown on arbitrary planes along vessels and important results are seen, like**:** Maximum difference velocity magnitude between all Newtonian and non-Newtonian models is 4% in all directions**.**

As confirmed in Berger [6], Pedley & Jou [5] papers, blood in low strain rates (below 100/s) shows non-Newtonian behaviour. And from studying distributions of strain rate on different conditions of vessel it has been observed that in most cardiac cycles (70%) strain rate is above (100/s); especially at the end**.**

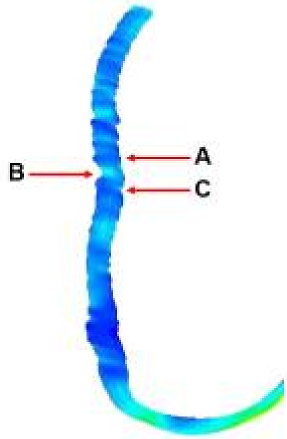

Figure 7: Choose 3 segments from first artery in velocity distribution diagram

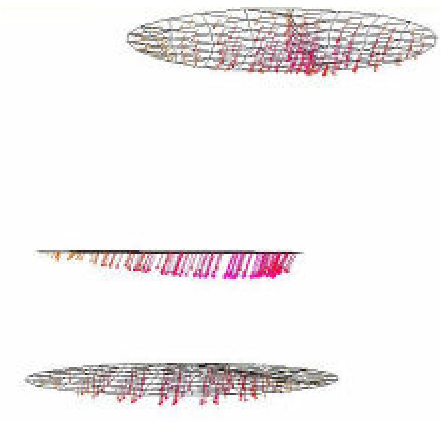

Figure 8: Showing the directions & intensity of velocity vectors

It should be considered that this study has been done, based on 60 beats per minute heart rate and low velocity (max 0.2 m/s). If heart rate exceeds to 100 beats/min (e.g. with moderate exercise) or the inlet velocity increases, the mentioned percent will definitely increase. This way it can be suggested that using Newtonian models is a good approximation and since WSS patterns for all Newtonian and non-Newtonian cases is the same, therefore if the model is changed during vessel analysis no disturbance occurs.

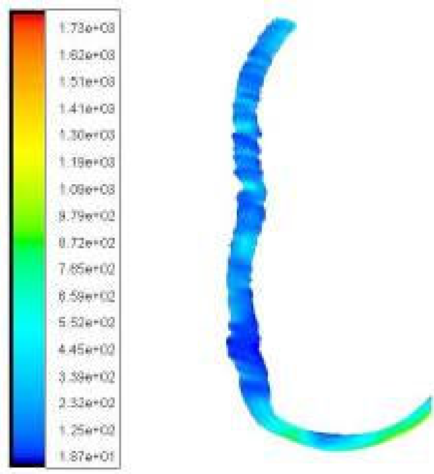

Figure 9: Strain rate distribution in 0.01 s after starting cardiac cycle (in Carreau model for first artery)

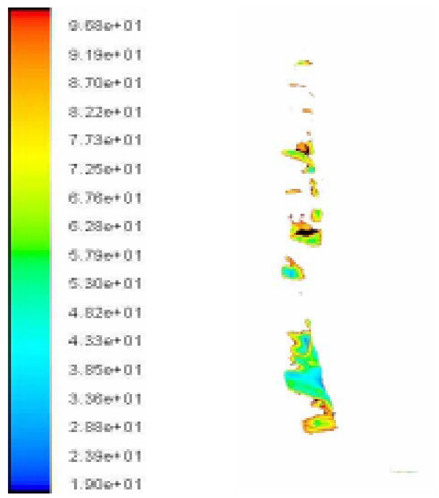

Figure 10: Area with strain rate under 100/s in the 0.01 s after starting cardiac cycle (in Carreau model for first artery)

8 Conclusions

This research explain the importance of study coronary arteries and also solving the governing equations of flow with steady & unsteady methods have been done on two normal right coronary arteries with considering of real samples and 3D analysis; also in laminar and turbulent flow regimes and Newtonian and non-Newtonian models. All comparisons between figures and images from vessels show that WSS forms have complicated patterns on vessel walls which result in meaningful changes during cardiac cycle. In the vessels examined, low WSS was seen at the beginning of vessel for a large part of heart cycle and high WSS was detected at the distal end and also in the curvature and narrowing area of vessel.

Sudden expansions result low WSS for most cardiac cycles.

Other important result of the paper is the diversity seen in coronary vessels and also existence of significant differences in their geometries. There is an inverse relation ship between vessel radius and WSS magnitude.

It was observed that either in steady case or unsteady one, patterns were similar for the vessels.

The main difference even in considering between Newtonian and non-Newtonian models was seen in WSS values and this was clearer in low and high inlet velocities.

Here the disadvantages of Power low model can be mentioned. In comparison with Carreau and Newtonian models, this model over estimates WSS for low inlet velocities and under estimates WSS for high inlet velocities. And also it seems that Newtonian model is a good approximation from medium to high ranges of WSS.

All this results plus Pedley [6] and Berger & Jou [5] theories about that blood shows Newtonian behavior in strain rates over than 100/s and obtain diagrams witch expressed 70% of vessels are in high ranges of strain rates; Here again using the Newtonian model for blood viscosity approximation is approved. Generally for simulating and studying WSS on vessels, Newtonian model can be sufficient but for more details and accuracy non-Newtonian behavior of blood should also be considered.

All the results are in good agreement with Barbara Johnson et al. papers in 2004 [3] and 2005[4].it also should be mentioned that, this study was done with some assumptions. One of the most important ones is the constancy of the mesh. If simulation is done with elastic vessel walls model and moveable mesh during the beat, better results will be gained.

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